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SPACE SHUTTLE ORBITER TRIMMED CENTER OF GRAVITY EXTENSION STUDY

VOLUME VI - SYSTEM DESIGN STUDIES

Ian O. MacConochie

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National Aeronautics and Space Administration

Langley Research Center
Hampton, Virginia 23665

SUMMARY

The practicality of extending the space shuttle orbiter c.g. envelope for various payloads was investigated by conducting systems design studies for several modifications to the aerodynamic shape of the vehicle. These modifications included several forebody shape changes, body flap planform changes, wing-fillet planform changes and various canards, both fixed and deployable. The changes in mass and design of the proposed aerodynamic modifications (principally involving airframe structural changes) are discussed in this document.

The removal of most of the current orbiter wing-body fillet with the substitution of a fixed canard near the forward portion of the removed fillet or replacement of the entire fillet with an extended length fillet appear to be the most viable structural changes and give substantial forward movement in trimmed c.g. capability. Forebody reshaping results in a small mass penalty but is relatively ineffective in improving forward trimmed c.g. capability. Ballisting with orbital maneuvering system in auxiliary tanks was also considered in the study.

INTRODUCTION

The longitudinal center-of-gravity range of the space shuttle orbiter for trimmed flight during entry, approach, and landing is limited. This puts a constraint on the allowable mass distribution of shuttle payloads. Greater latitude in forward c.g. would be advantageous for some payload designs. In an effort to extend the center-of-gravity envelope, an aero/systems study was undertaken at the Langley Research Center to determine the feasibility of developing modifications which would give the greatest increase in forward c.g. extension with a minimum impact on the existing orbiter systems design and payload capability. Modifications which were studied included changes in fuselage nose shape and wing fillet planform and the addition of fixed canard surfaces. Systems design analyses were undertaken to determine the corresponding mass penalties. Aerodynamic heating tests and analyses (reference 1) provided information on the impact of the modifications on thermal protection system requirements. Wind tunnel force and moment tests were conducted across the speed range to assess the aerodynamic effectiveness of the modifications in extending the center-of-gravity envelope. Aerodynamic characteristics of the modifications are presented in references 2 to 5.

This report presents the results of systems design studies. The major guideline of the study was that the modifications or retrofits under consideration should have a minimum impact on the orbiter subsystems design, mass, and development schedule. Since the major forward center-of-gravity trim requirement occurs in the Mach number range of 4.0 to 6.0, the study emphasis was placed on those modifications considered to be the most effective in this speed range. Most of the study effort, therefore, focused on modifications to the forebody, and the wing fillet. These modifications consisted of changes in the entire fillet shape or replacement of a portion of the fillet with a canard.

SCOPE OF SYSTEMS STUDIES

Several types of modifications were considered during the study. Forebody shaping was found to be effective in providing additional hypersonic trim capability, however, subsonic trim capability was relatively unchanged. Although subsonic trim with a forward center of gravity was adequate, the trim lift losses associated with the forward c.g. would increase the subsonic minimum design speed. In conjunction with the forebody modifications, an increase in body flap span was studied. This modification is a promising approach to provide the necessary subsonic trim without compromising the landing speed.

The most effective modifications through the speed range were found to be in the area of the wing fillet. By making the fillet removable it can be replaced with various modified shapes to provide the necessary forward center-of-gravity trim capability extension. Several changes in the fillet planform and several canard shapes were studied to replace a portion of the fillet. Two folding canard concepts were studied from a systems standpoint only.

As a result of preliminary aerodynamic studies, an extended fillet and a canard were selected for major emphasis for the remainder of the study.

PRESENTATION OF RESULTS

Forebody Modifications

In the initial phase of the study, two forebody modifications were examined. The first approach (fig. 1) consisted of raising the nose 50.8 cm to vary the camber. The upsweep of the forebody was constrained to body frames forward of station 385 to avoid an impact on the cabin pressure vessel moldlines (all body stations are inches). A change in the lengths of the nose gear drag and retraction linkages would also be required. The forebody cross-sections were not altered, but simply moved upward to produce the upsweep. If this change was incorporated during initial construction of the forebody, the mass penalty would be minimal, but if retrofitted, would involve a mass penalty estimated at 227 Kg. The aerodynamic gain in forward c.g. trim capability is about 0.5 percent of body length. The corresponding available forward vehicle mass c.g. movement for the retrofit design is estimated to be 0.12 percent, leaving a net gain of 0.38 percent of body length for c.g. forward movement.

The second modification consisted of increasing the forebody width by adding a built-up structure and additional TPS thickness to obtain new contours (fig. 2). The mass penalty is 186 Kg and the aerodynamic net gain in trim capability is about 0.3 percent of body length.

The favorable effects of these changes in forebody camber and width suggest that a combination of these modifications would provide the maximum favorable trim effect. The resulting forebody contours are shown in figure 3. The aerodynamic data of reference 2 indicates a net gain in forward c.g. trim capability of about 1.0 percent of body length. The retrofit of this revised forebody shape would require a buildup of the ring frame structure and a slight increase in TPS area and thickness which would increase the orbiter dry mass by an estimated 500 Kg. Although the maximum width forebody provided additional forward c.g. trim capability at hypersonic speeds, it is not expected to provide an increase in subsonic trim capability. In order to provide increased subsonic trim capability, a body flap span extension was designed in conjunction with the maximum width forebody (fig. 4). Since the spanwise extension was needed for trim at subsonic speeds only, and would require additional thermal protection during entry, the body flap extensions were hinged (fig. 4.b.) so that they could be stowed during entry and deployed at subsonic speeds. The mass increase due to the body flap extension is estimated at 606 Kg. Probable interactions between the RCS system plumes and body flap extensions when in the up position would have to be investigated. Because of the relative complexity the above modifications for the amount of c.g. envelope gain, this approach was abandoned.

Fillet Modifications

A number of fillet modifications were studied, ranging from fillet removal to replacement of the baseline fillet design with a larger fillet extending forward onto the forebody section.

As shown in figure 5, removal of the fillet requires that it be replaced by a small fairing in order to cover the original attachment (or scar) area and make a transition from the orbiter bottom-to-side surface. Alternatively, a ring frame redesign would be required to provide corner radii (fig. 8). The scar weight penalties for making the fillet removable are shown in figure 6 for the major orbiter sections; namely, forebody (section A), mid-fuselage (section B), and wing (section C). Some of the mass increase is associated with strengthening the frames in zone B (slightly larger caps) to accommodate the loads imposed by a canard; however, most of the mass increases are due to additional fasteners and locator surfaces to make the joint a purely mechanical one. As shown in figure 7, a change in the leading-edge spar cap design in zone C would facilitate retrofits in this area.

In the aerodynamic investigations of reference 2 to 5, several alternate fillet configurations were studied, but the system studies focused on the most promising approach shown in figures 8 to 10. This fillet was extended forward of the baseline fillet to the region of the forebody. As can be seen in figure 9, the fillet contours were smoothly blended into the orbiter bottom surface in order to minimize aeroheating effects. The mass of the extended length fillet was estimated on the basis of a construction similar to the baseline fillet. The resulting mass is 470 Kg heavier than the baseline fillet and moved the orbiter c.g. mass forward by 0.1 percent of the body length. Aerodynamically, this modification gave a substantial gain in forward c.g. capability for the orbiter and therefore was one of the prime candidates for further systems studies.

Although the study emphasis was on forward extension of the trimmed c.g., the ability to remove the fillet suggests that a much more rearward c.g. could be tolerated without sacrificing longitudinal stability. Fillet removal results in a dry mass reduction of 747 Kg, which could be reflected in increased payload providing the payload is one with an aft c.g.; vehicle c.g. moves rearward 0.2 percent of body reference length for this modification. This is fractionally small compared to the gain in aft c.g. payload envelope due to changed aerodynamics (ref. 5).

Canard Modifications

Several canard designs were investigated including movable and fixed types. One of the study tasks was to examine the impact of replacing the baseline fillet with a fixed canard to determine if the modification would be lighter and more effective. The canard (fig. 11) was found to be slightly more effective aerodynamically, but an increase of 34 Kg in overall orbiter mass resulted in spite of partial fillet removal.

The structural aspects of a fixed canard blended with the baseline fillet was examined (fig. 12). This canard was limited to X-stations between 534 and 807, the aft stations being the present interface between the Grumman and General Dynamics Corporation fillet sections. The leading edge of the canard extends onto the forebody and involves a small fairing at the Rockwell International nose section (fig. 12a, zone A). The structural concept is shown in figure 12(b). As shown by the moldlines in figure 12(c), the canard bottom surface is faired in with the orbiter bottom surface with a buildup on the orbiter body TPS.

The geometry of the canards is as follows:

Planform area, both canards (outboard of Y_o = 108)-------27.3 meters^2

Wetted area, both canards---------------------------------59.8 meters^2

Leading edge sweep--55^o

The aero-loading assumptions for spars and ribs were 4.5 KN/m^2 limit and 6.3KN/m^2 ultimate. The spanwise loading distribution was taken as 288 N/cm from station Y_o = 164 and was assumed to decreased linearly from the latter station to zero at the canard tips, i.e., station Y_o = 244. The canard covers were designed for 17.4 KN/m^2 to allow for buffet loads. Actual flight conditions assumed to represent the highest loading condition are given below:

MACH NUMBER----------------------------------4

RELATIVE VELOCITY---------------------------1250 m/sec

DYNAMIC PRESSURE (Free stream)--------------9193 N/m^2

NORMAL ACCELERATION-------------------------10.8 m/sec^2

ALTITUDE-------------------------------------26 Km

FLIGHT PATH ANGLE--------------------------- -5^o

ANGLE OF ATTACK----------------------------- 8^o go 12^o

TRAJECTORY----------------------------------1404 D

Material used for the canard is 2024 aluminum with an allowable stress of 479 KN/m^2 to assure design life goal and preclude adverse aeroelastic effects. An allowance of 13 Kg/m^2 average was made for thermal protection including leading edge pieces. Leading edges are reinforced carbon composite while remainder of the canard is low density reusable surface insulation. Aluminum was used for the canard structure as a low cost approach. In the event that a thermal analysis indicated excessive temperatures for the aluminum structure, an alternate material could be used such as titanium for approximately the same weight.

The blended canard addition resulted in an orbiter net mass increase of approximately 1030 Kg. The component mass breakdown is shown below:

		Kg
SPARS		71
RIBS		81
COVERS		191
TOP FILLET		36
ATTACHMENTS		11
TPS		292
	SUB TOTAL	682
CANARD (BOTH SIDES)		1364
FRAME MODIFICATIONS		25
LANDING GEAR MODIFICATIONS		21
	TOTAL CANARD MASS =	1410
	NET PENALTY =	1030 kg

Aerodynamic testing of this type of canard (ref 3) indicated that it is one of the most effective retrofits studied and in fact represents an overdesign from an aerodynamic standpoint exceeding the design specifications for subsonic longitudinal stability margin. For this reason the canard was scaled down utilizing the point design information generated above. The resulting mass penalty is 681 kg. A comparison of the planform of the scaled-down canard with the point design is shown in figure 13.

The re-sized canard, although heavier than the extended length fillet of figures 8 to 10, has a smaller impact on the orbiter structure since it affects only the area between stations 582 and 807, whereas the fillet impacts the area from station 300 to station 1061.

In addition to fixed installations, two deployable canard designs were investigated (figs 14 and 15). This approach would have a minimum impact on the fore- and mid-body thermal protection systems during the peak reentry heating. Further, with a foldable feature the orbiter could be configured for the mission prior to entry. The fold-down canard with hingeline at the cargo bay door resulted in a restriction in cargo bay door opening. Its mass is 544 kg with a forward movement of 0.19 percent vehicle c.g. The fold-up canard did not obstruct the cargo bay opening angle but the complexity of the interfaces at the canard hingeline necessitated the use of two smaller doors which deploy with the canard in order to smoothly fair the installation for supersonic and subsonic flight with the existing fillet. Its mass is 689 kg with a 0.24 percent forward movement in vehicle c.g. The deployable type of canard would provide more operational flexibility but would be more complex and costly than the fixed surface designs.

BALLAST

Ballasting for c.g. management and control was briefly investigated. This could be achieved by the installation of tanks in the fillet or body mid-section of the orbiter (fig 16). These tanks would be connected to the On-Orbit-Manuevering-System (OMS) and would contain propellants identical to the OMS engine supply (or alternatively, a purge fluid not detrimental to the OMS system).

At entry the fluid or a portion thereof, would be either left in the forward mounted tanks or alternatively transferred to the OMS pods tank for an aft ballast. Based on an orbiter entry mass of 84,822 kg and a total fluid ballast of 5600 kg, the maximum entry c.g. adjustment possible in this way is 2.66 percent.

In an ascent abort case, based on an orbiter aborted mass of 112,000 Kg, the orbiter c.g. is 69.4 percent for the most aft payload location and fully loaded OMS system. However, with full ballast (i.e., maneuver reserves) in the forward auxiliary OMS tanks, the vehicle c.g. is moved forward by 1 percent. This reduces the amount of OMS dump required for flight in an abort situation.

For a forward cargo mission, the OMS reserves would be located aft in the OMS pods where the propellants are immediately accessible to the maneuver engines for L/D modulation (i.e., the engines could be used principally between the 3,700 to 1,000 m altitudes for energy management in order to meet the Approach and Landing Conditions, if required).

DISCUSSION

The results of the systems design studies are summarized in Table I. All of the proposed modifications studied providing forward c.g. extension involved an increase in vehicle dry mass and a fractional change in the empty vehicle c.g. in the forward direction.

In almost every case the aerodynamic change intended to expand the allowable cargo limit (fore or aft) resulted in an increase in orbiter mass which meant a small loss in payload capability. The single exception to this was the removal of the baseline fillet in which case the aft cargo c.g. was extended rearward with a payload gain of approximately 747 Kg.

Reference 4 indicates that the most effective aerodynamic modifications to extend the forward trimmed c.g. of the orbiter are the extended fillet (fig. 8) and an in-fillet canard (C-3 in fig. 13) sized to maintain the subsonic longitudinal stability requirement. The maximum width forebody (though effective at hypersonic speeds) would require an auxiliary subsonic trim device in order to prevent higher landing speeds with forward c.g. locations. The extendable body flap studied herein in combination with the maximum width forebody was found to be heavy (1606 Kg) in comparison to the masses and aerodynamic gains of the fillet and canard. The extended fillet, S-2, was the lightest of the more favorable retrofits, however, it would require the largest scar mass on the orbiter body. A blended in-fillet canard (C-3) gives the least systems impact, since it affects only a small section of the orbiter baseline fillet (i.e., from station 582 to 807); however, it is heavier than the extended fillet by 211 Kg. The vehicle scar mass for either the extended fillet or the canard is considered to be small.

From the standpoint of operations and systems design, it was assumed in this study that the entry c.g. for the orbiter can be predicted in advance of the mission. Therefore, it is assumed that sufficient turn-around time would be available for removal of a canard installation on the ground or, that a second orbiter would be available, configured for special missions with the fillet or canard. As an alternative to the bolt-on retrofits, the two folding canard concepts studied could be utilized as permanent installations, minimizing the ground turn-around effort, however, the installation would constitute a considerable mass penalty on missions for which a forward c.g. payload is not flown.

SUMMARY OF RESULTS

The results of the systems designs studies of several aerodynamic shape modifications intended to extend forward center-of-gravity envelope of the shuttle orbiter may be summarized as follows:

1. For small forward extensions of the c.g. envelope, re-shaping the forebody could be accomplished with minimum mass penalties.

2. Increasing forebody width, camber, and length to the maximum extent possible increases c.g. capability but is heavy and requires auxiliary trim devices at subsonic speeds.

3. Removal and replacement of all, or a portion of the baseline fillet, with a retro-fit trim device is a relatively simple, lightweight modification. The scar mass associated with making the fillet removable is estimated at 50 Kg.

4. The lightest mass and most effective retro-fit involves an extended length fillet designed to replace the baseline fillet. This fillet increases the vehicle mass by 470 Kg and involves a slightly greater scar area than that left by the original fillet.

5. The simplest of the more effective retro-fits, from a mechanical standpoint, is the in-fillet canard which replaces a portion of the baseline fillet (between manufacturers interfaces) with a canard that is blended into the original contours. This installation is heavier than the extended fillet by 211 Kg.

6. Deployable canard surfaces were found to be heavy (544 to 689 Kg) and would constitute a permanent weight penalty for the orbiter on all missions.

7. Ballasting with OMS reserves is a possible alternative to c.g. management but it must be assumed that up and down cargo capability would be reduced for mission-limited cargo masses by the amount of the ballast and added tankage.

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2. Bernot, Peter T.: Space Shuttle Orbiter Trimmed Center-of-Gravity Extension Study, Volume I - Effects of Configuration Modifications on the Aerodynamic Characteristics of the 140 A/B Orbiter at M=10.3. NASA TMX - 72661, 1976.

3. Phillips, W. Pelham: Space Shuttle Orbiter Trimmed Center-of-Gravity Extension Study, Volume II - Effects of Configuration Modifications on the Aerodynamic Characteristics of the 140 A/B Orbiter at Transonic Speeds. NASA TMX - 72661, 1976.

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5. Scallion, William I., and Stone, David R.: Space Shuttle Orbiter Trimmed Center-of-Gravity Extension Study, Volume IV - Effects of Configuration Modifications on the Aerodynamic Characteristics of the 139B Orbiter at Mach 20.3. NASA TMX - 72661, 1976.

TABLE I.- WEIGHT AND C.G. SUMMARY

MODIFICATION	FIGURE NO.	ΔPLANFORM AREA m^2	ΔWEIGHT KG	ΔXC.G. MASS $\%L_{ref}$
FOREBODY				
Minimum Camber B2 *	1	--	+22	Negligible
Width Addition B3 *	2	0.88	+181	-0.16
Maximum Width and Camber B4*	3	6.97	+500	-0.30
FILLET				
Extended Length S2 *	8-10	12.44	+470	-0.10
CANARD				
With Fillet Removed C2*	11	-1.58	+33	-0.20
Blended C4*	12	18.95	+1029	-0.36
Re-Sized	13	12.45	+681	-0.23
Fold-Down**	14	9.01	+544	-0.19
Fold-Up**	15	8.73	+689	-0.24

* Langley Wind Tunnel Test Designations
**Refers to Stowed Position

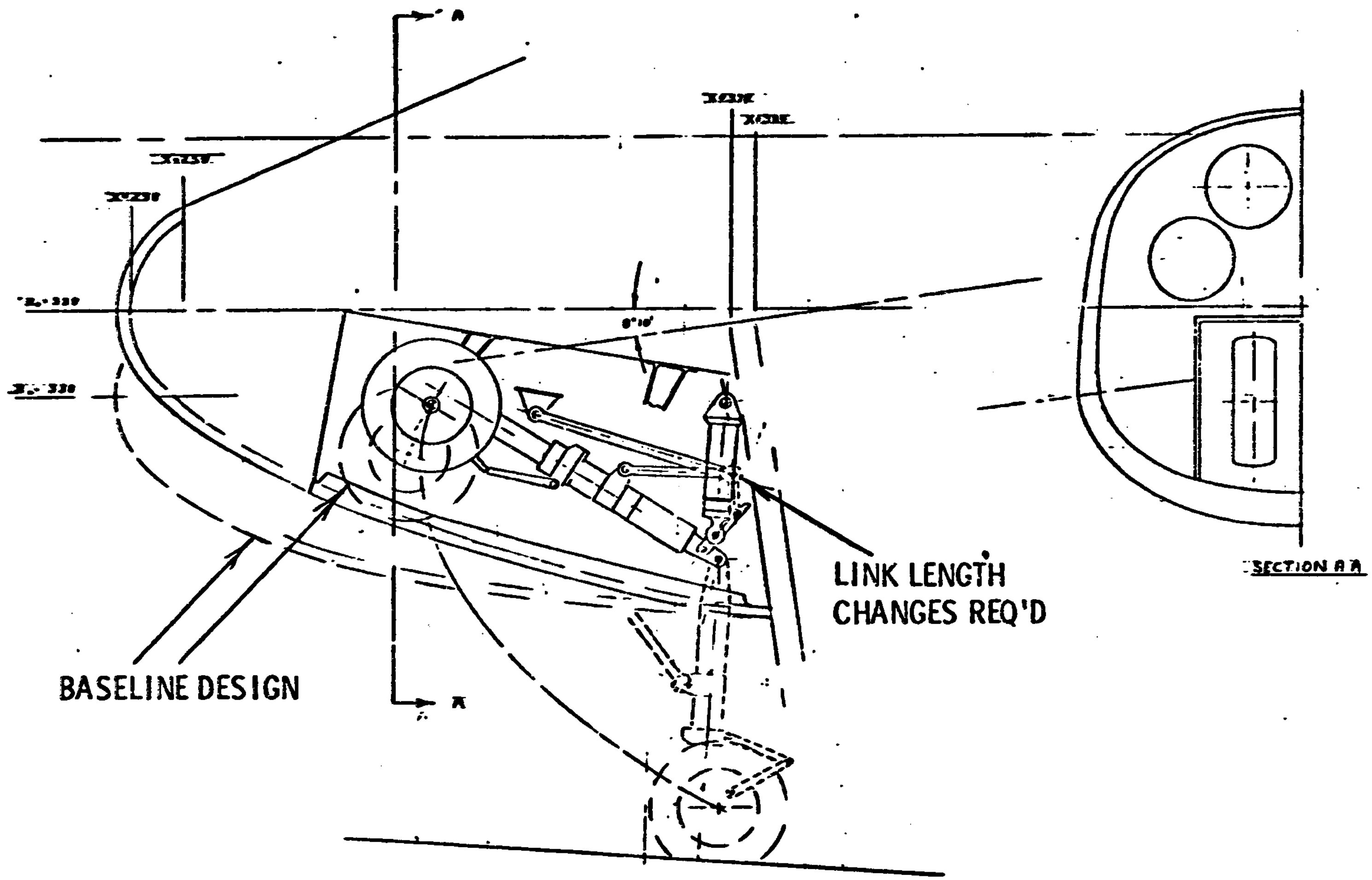

Figure 1 - B-2 Cambered forebody

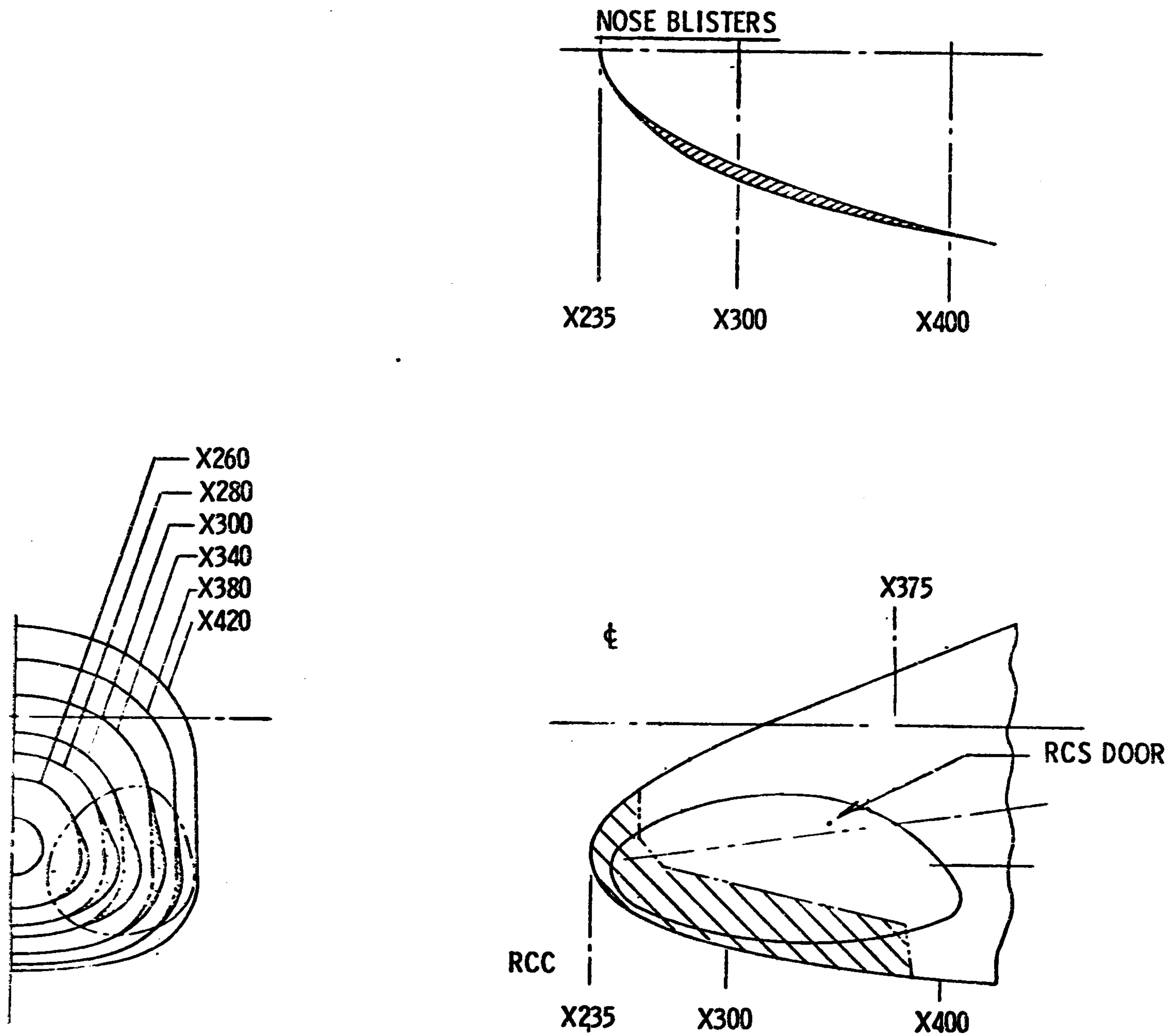

Figure 2 - Increased width forebody

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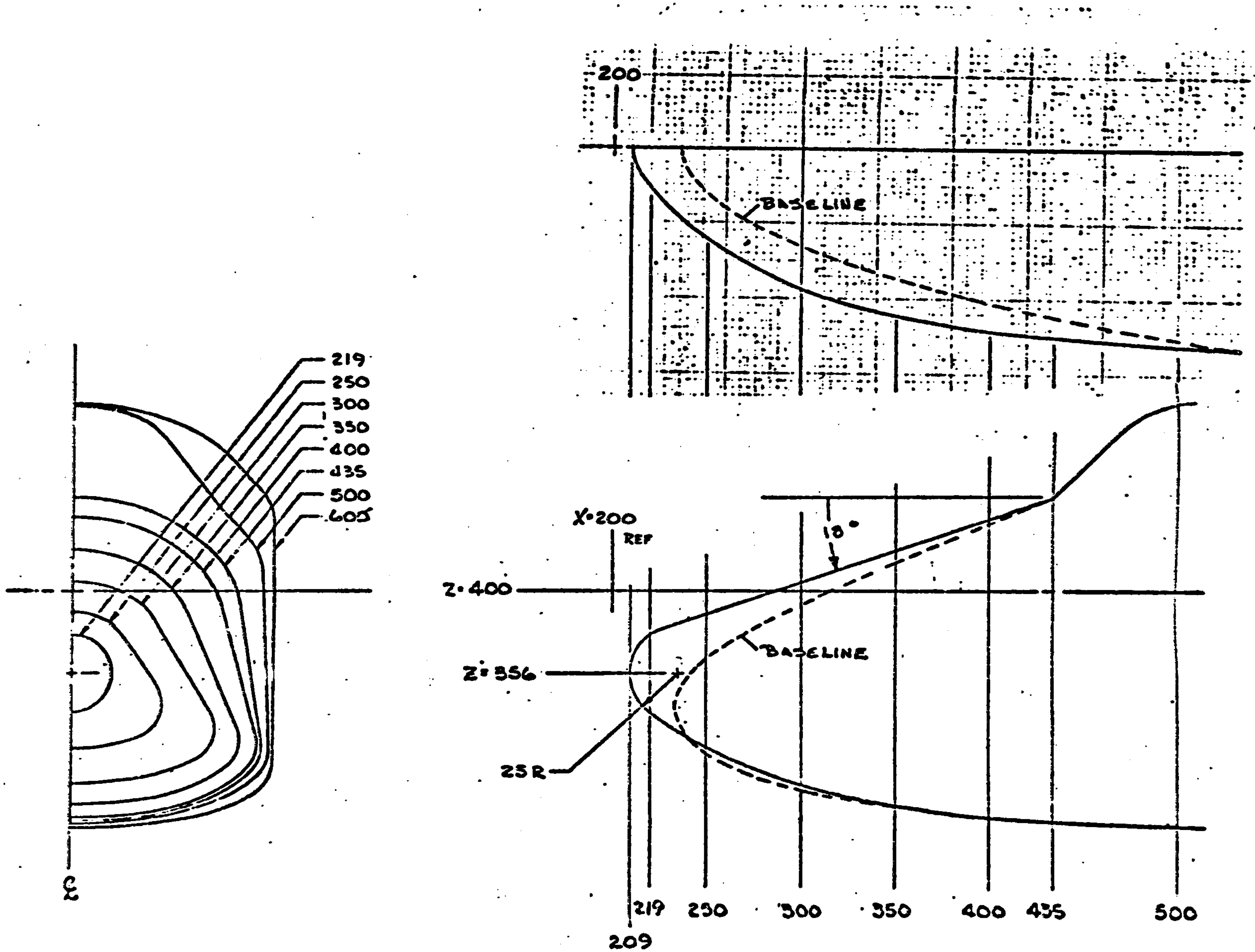
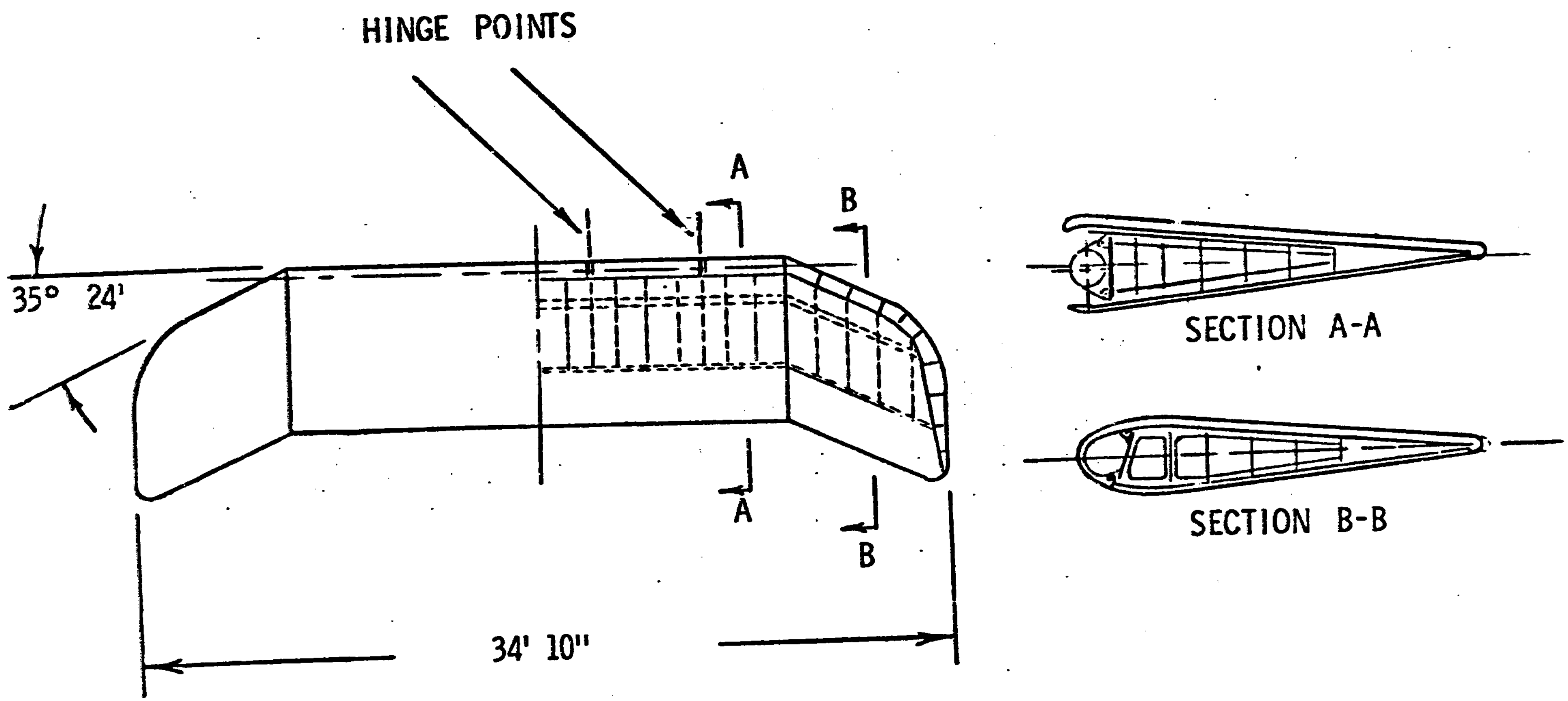
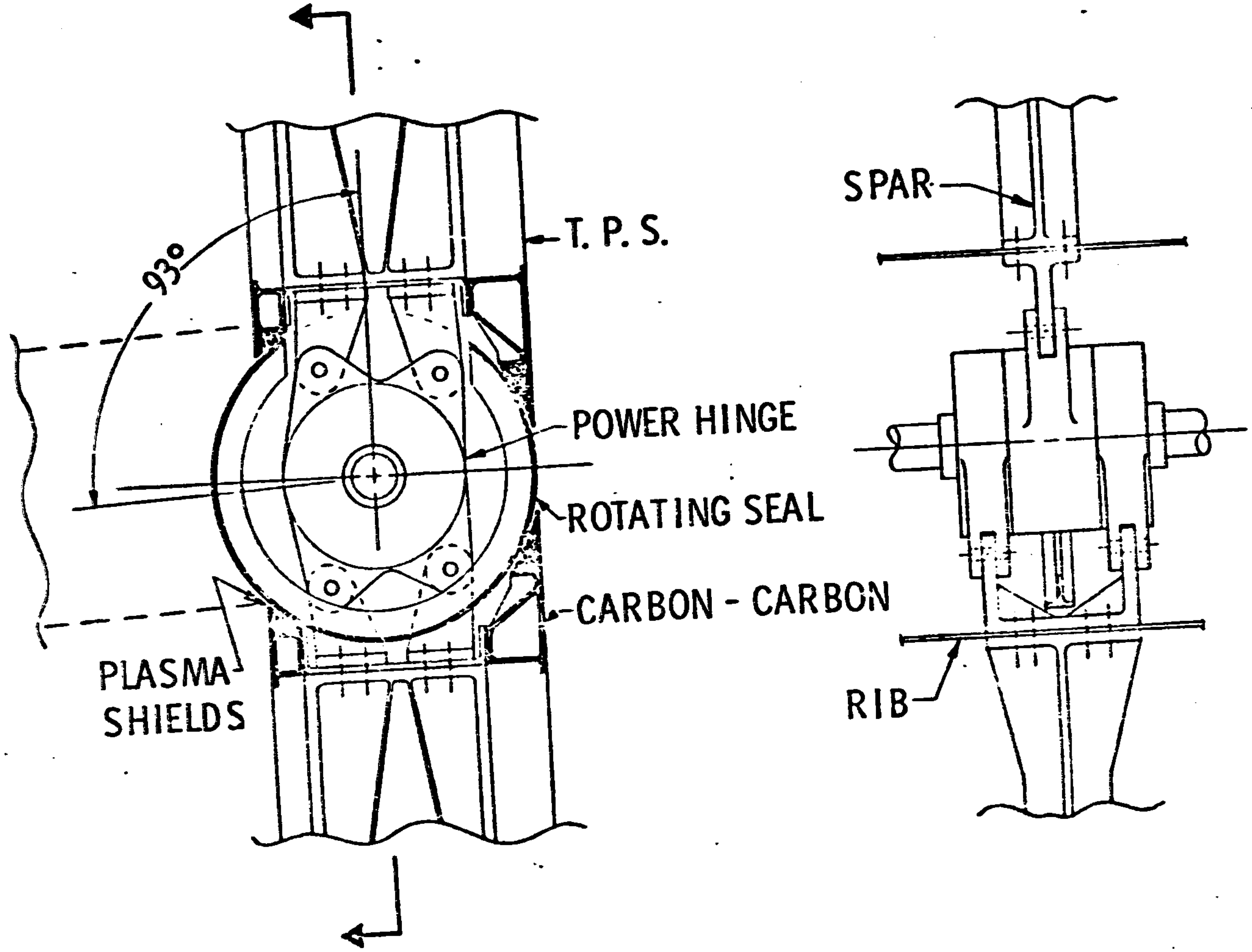


Figure 3 - Maximum width forebody (B-3) with increased camber and extension



(a) Span extension
Figure 4 - Body flap modification



(b) Body flap variable geometry hinge

Figure 4 - Continued

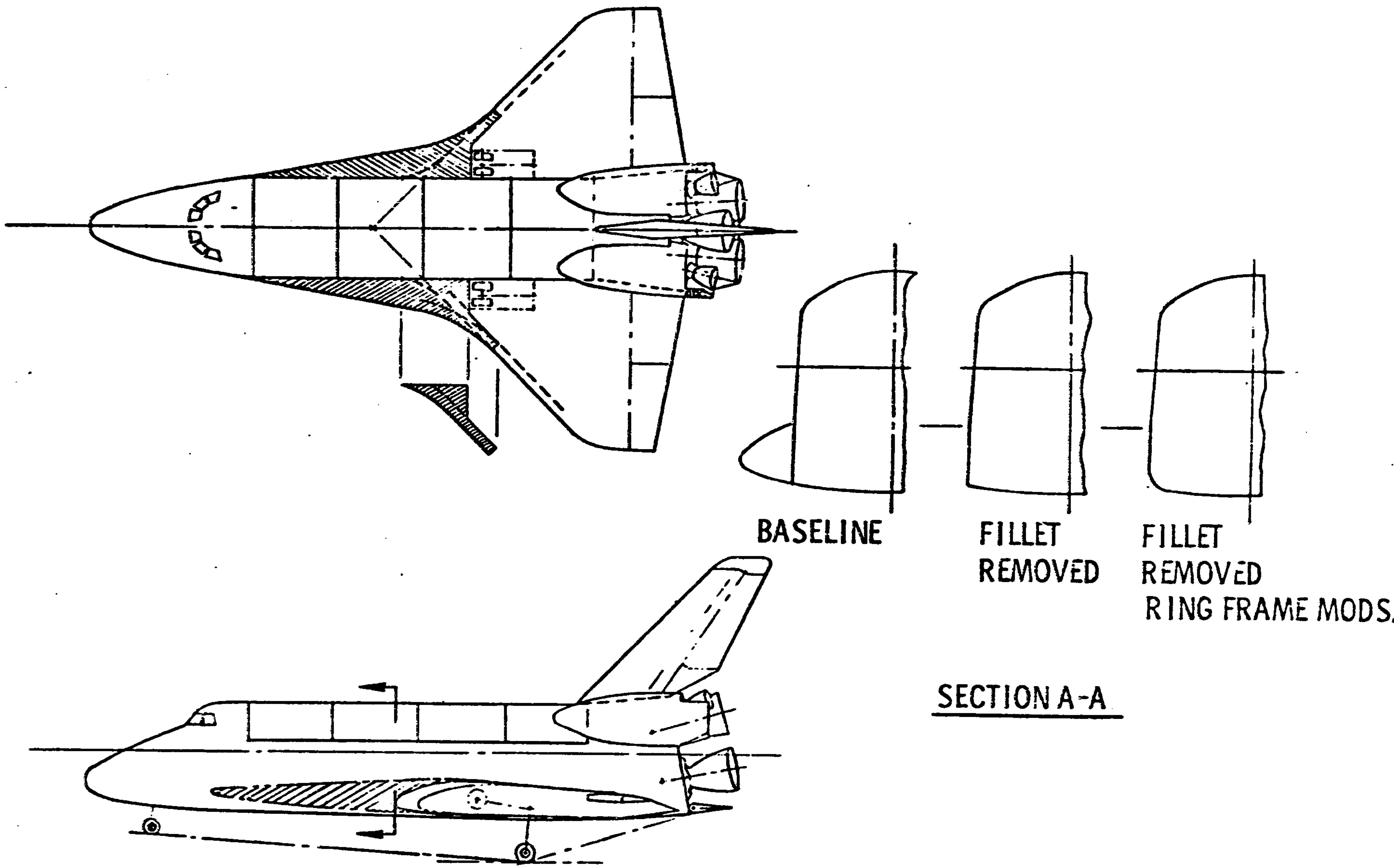
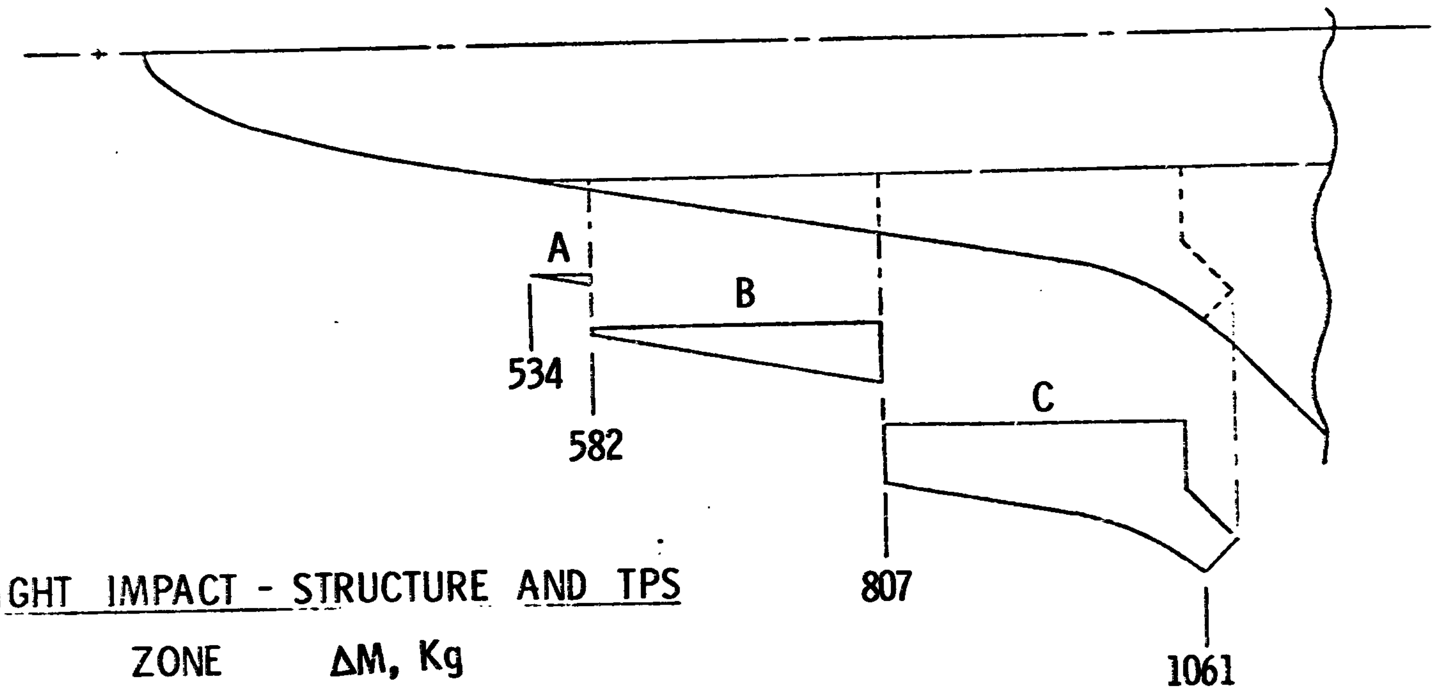


Figure 5 - Removable leading-edge fillet



WEIGHT IMPACT - STRUCTURE AND TPS

ZONE	ΔM, Kg
A	0.5
B	18.2
C	31.8
TOTAL (2 SIDES)	50.5

Figure 6 - Removable fillet scar-weight penalties

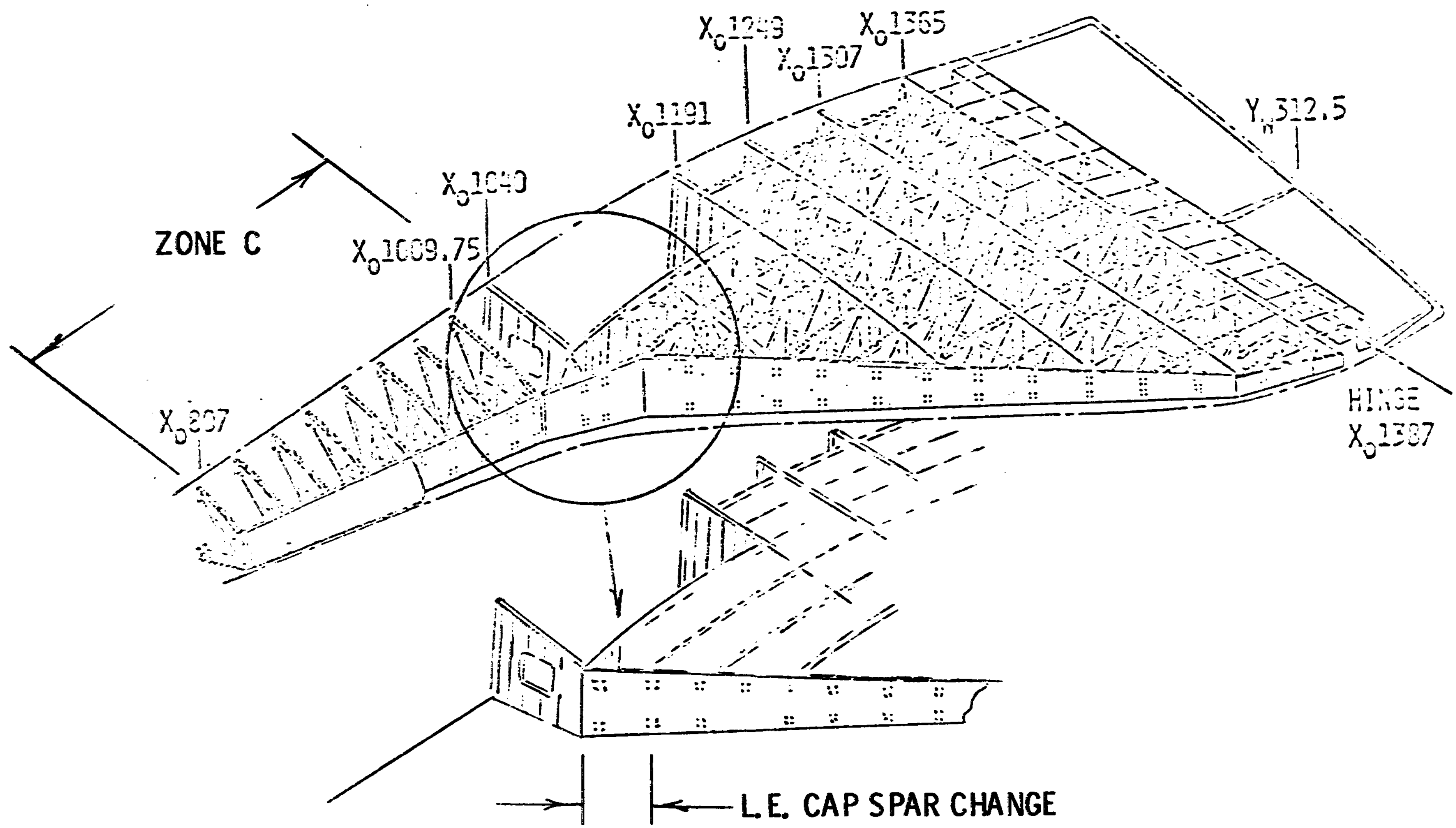


Figure 7 - Wing leading edge spar change designed to facilitate fillet retrofits.

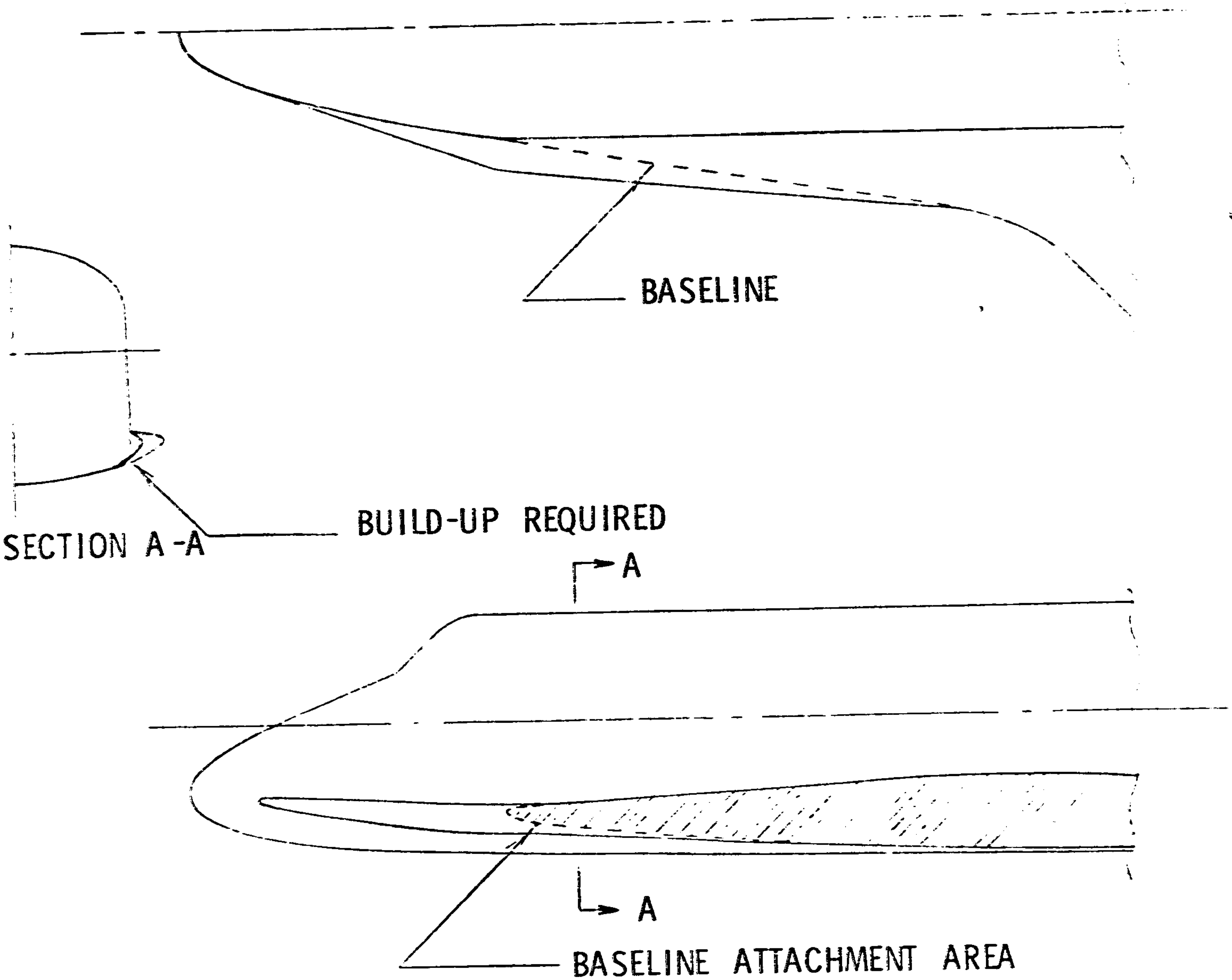


Figure 8 - Extended fillet (S-2)

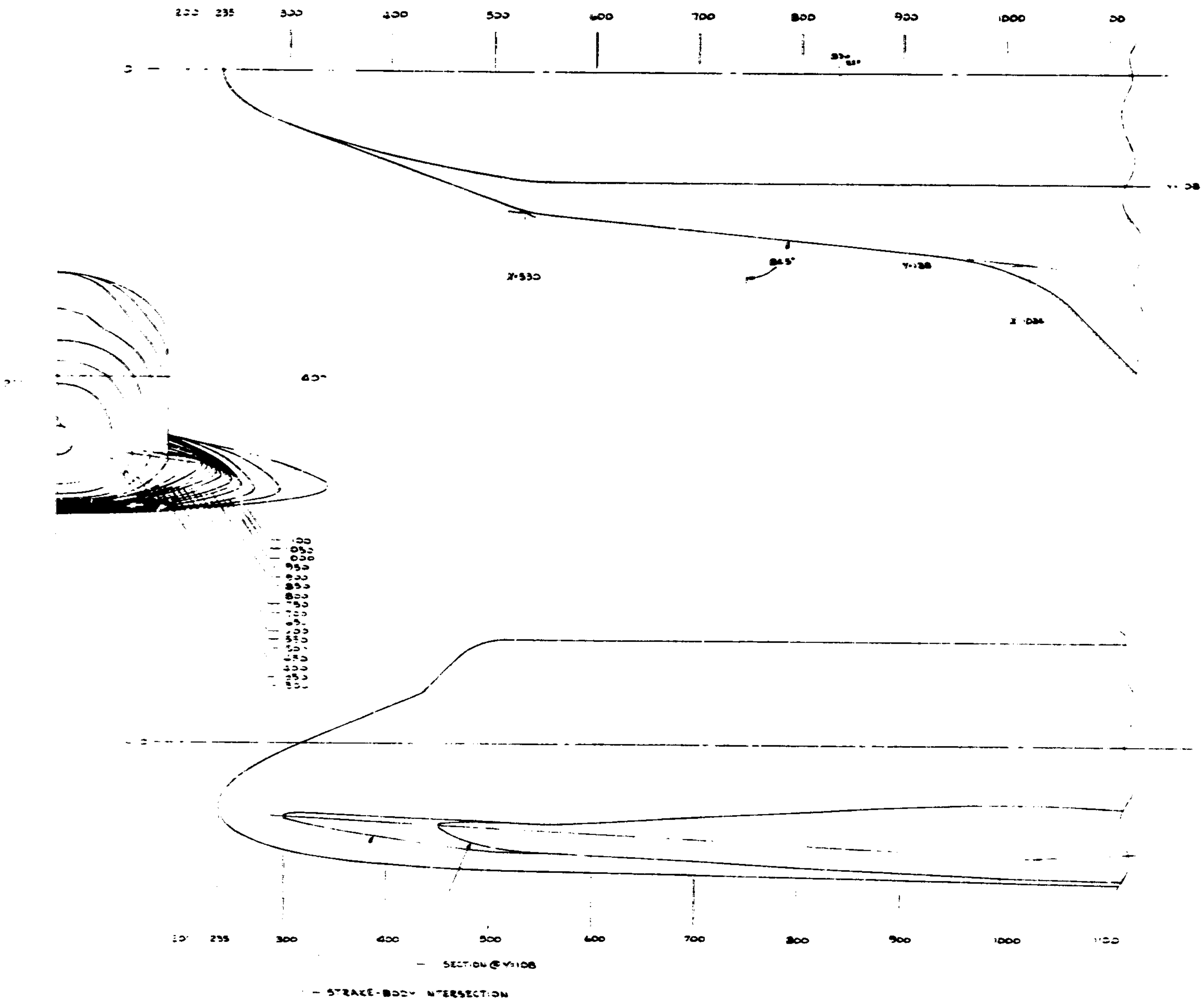
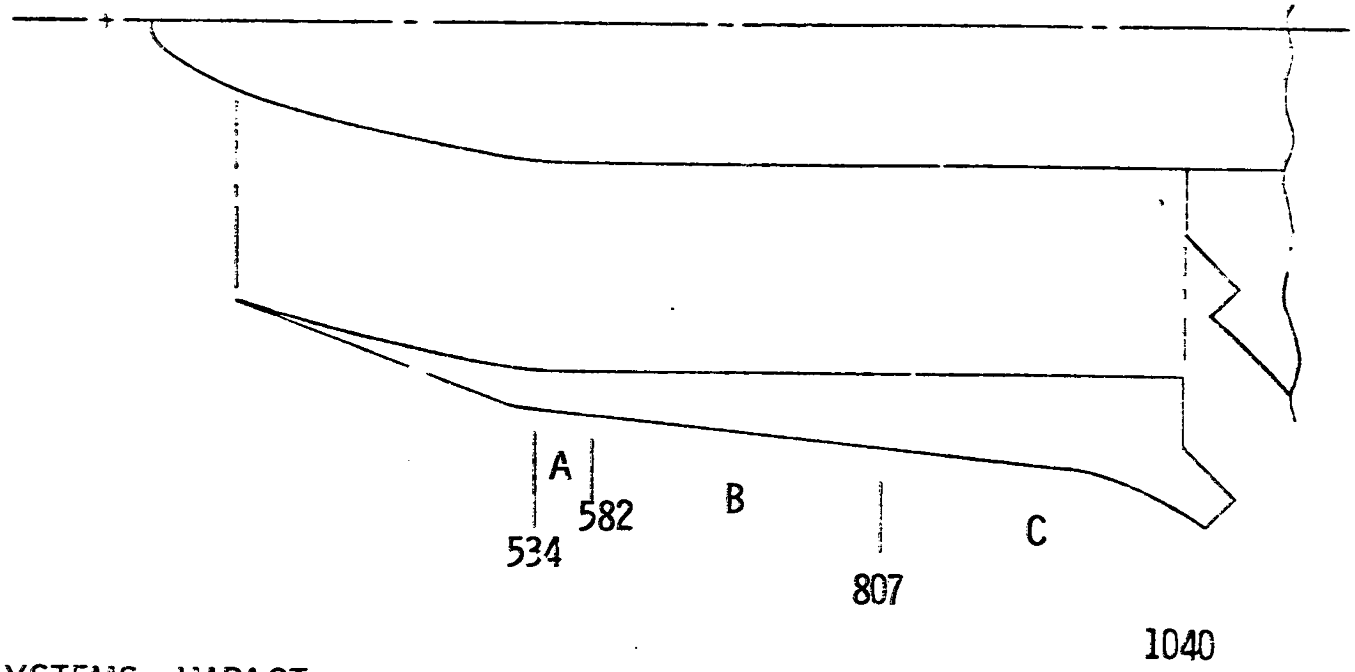


Figure 9 - S-2 Fillet moldlines



SYSTEMS IMPACT

Δ W = + 470kg

Δ C. G. = 0.1 PERCENT FWD

Δ AREA (PLANFORM) = + 12.5 m^2

Figure 10 - S-2 Fillet stations and mass properties impact

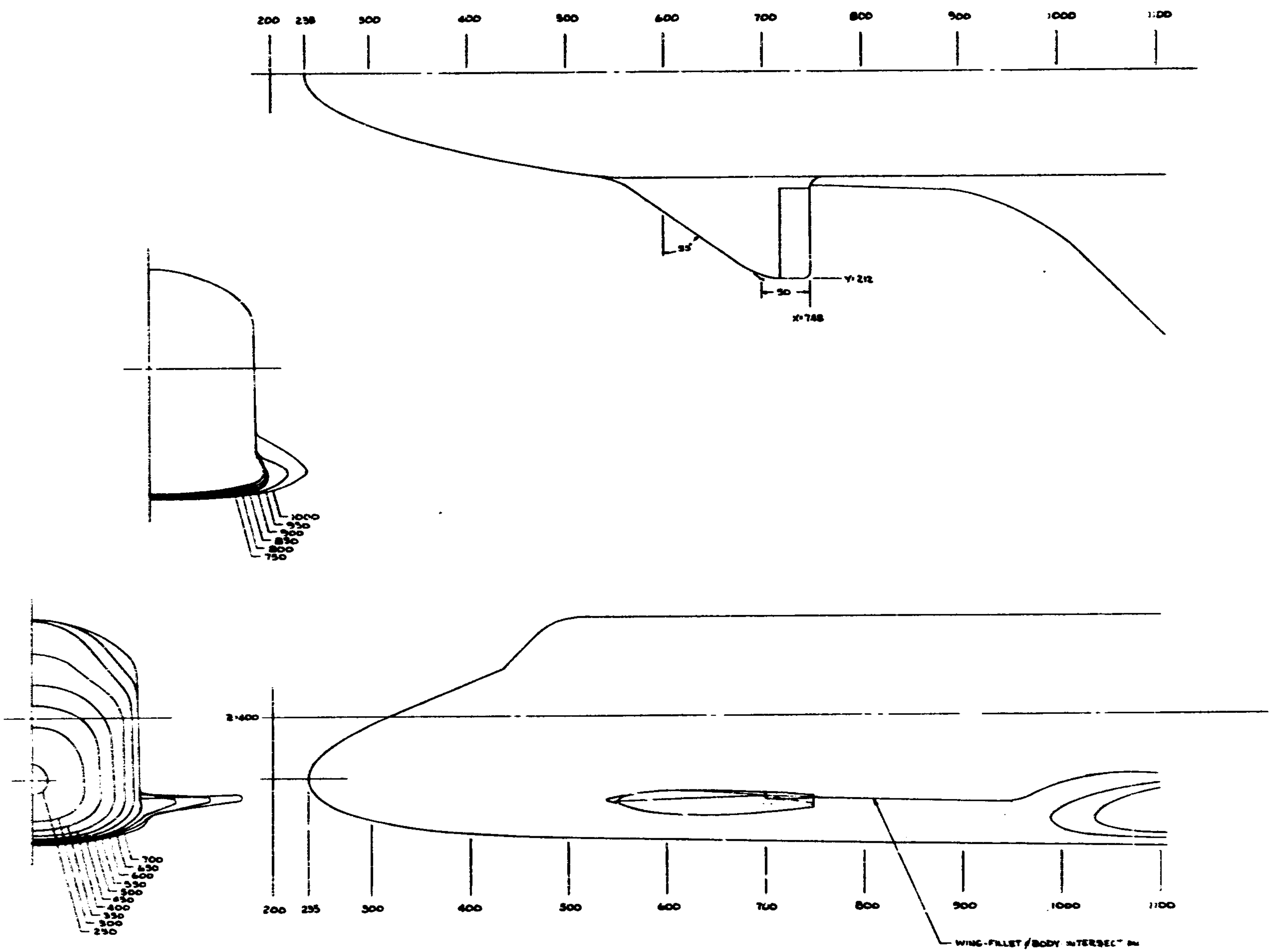
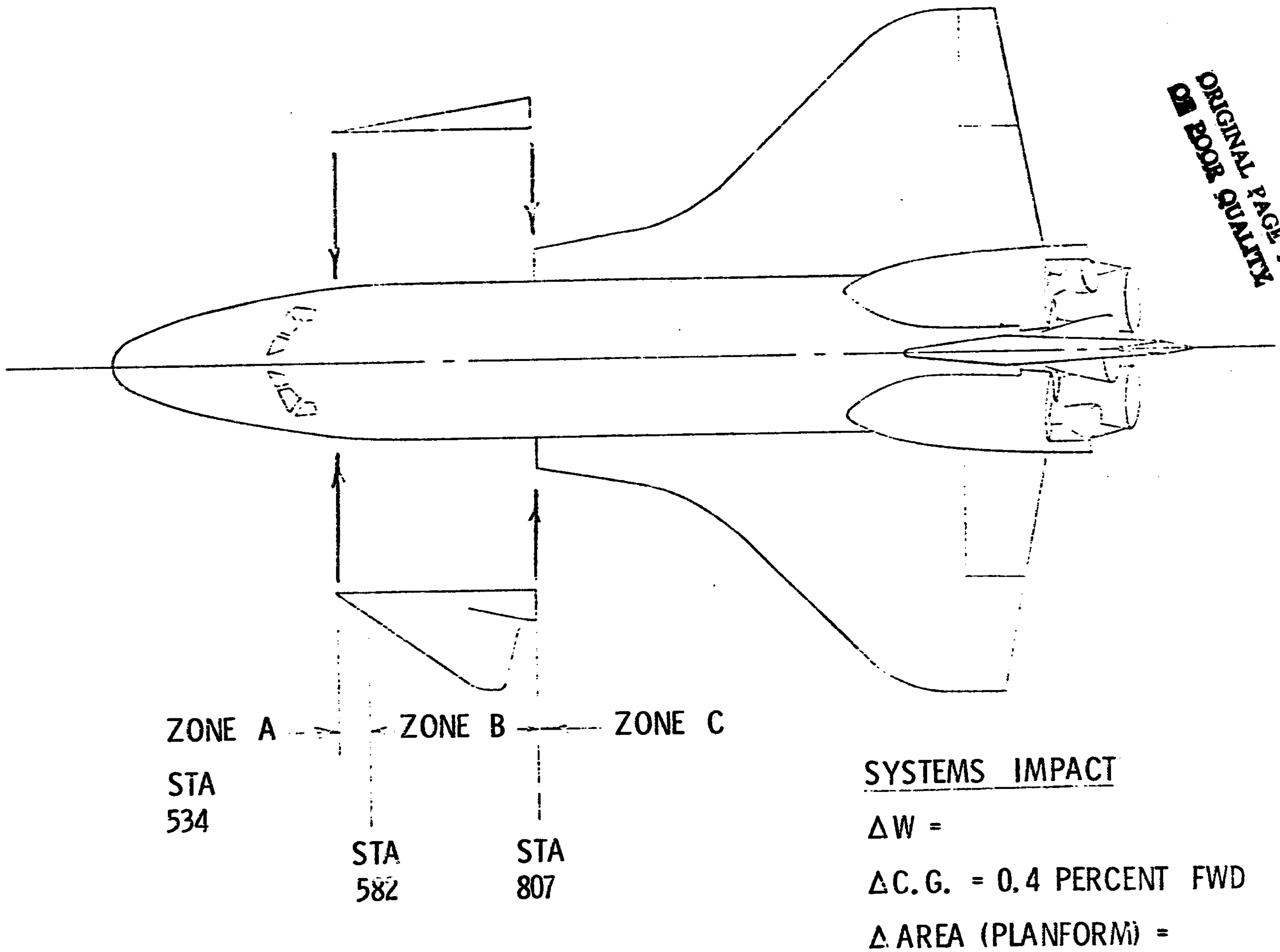
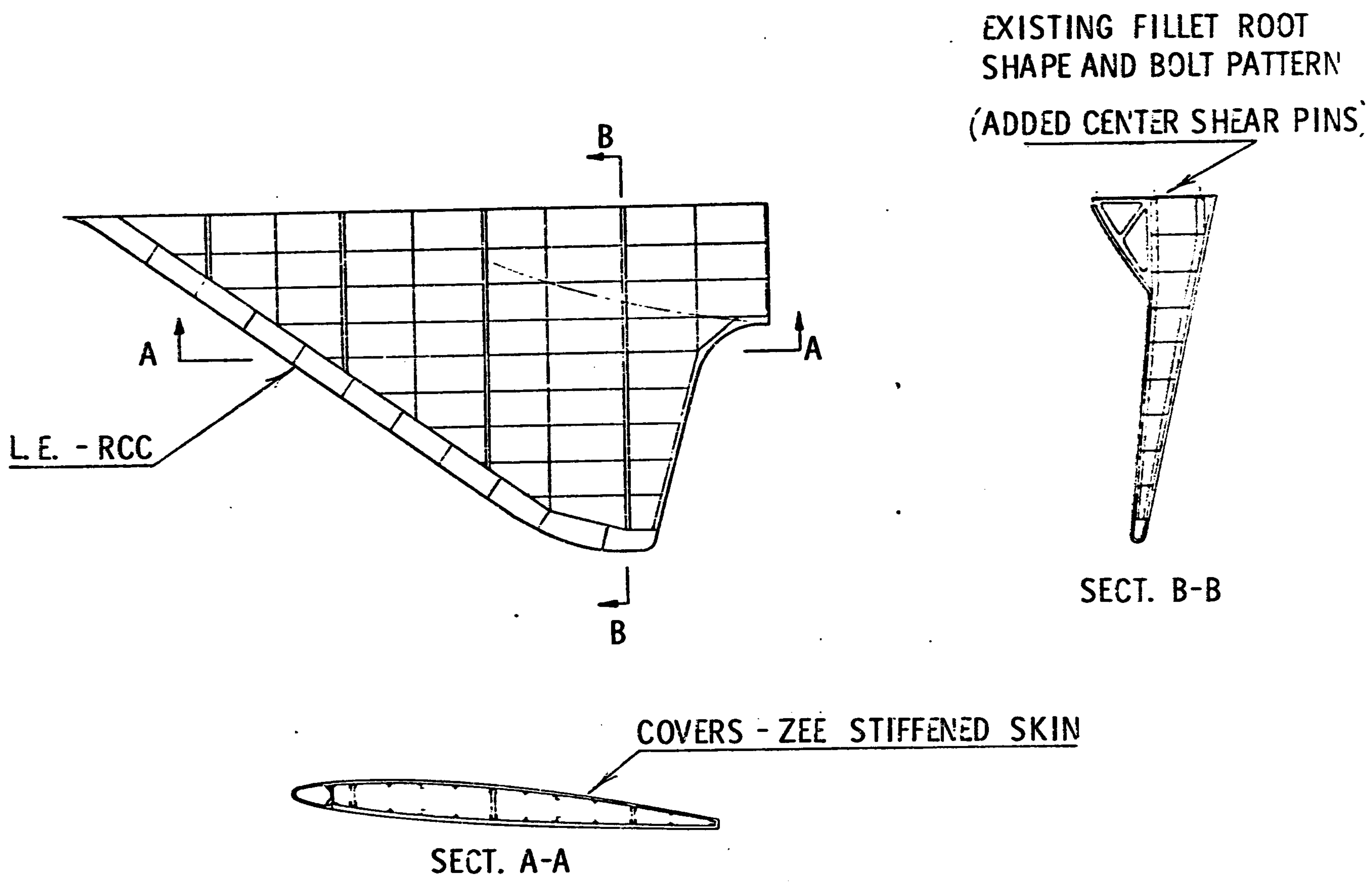


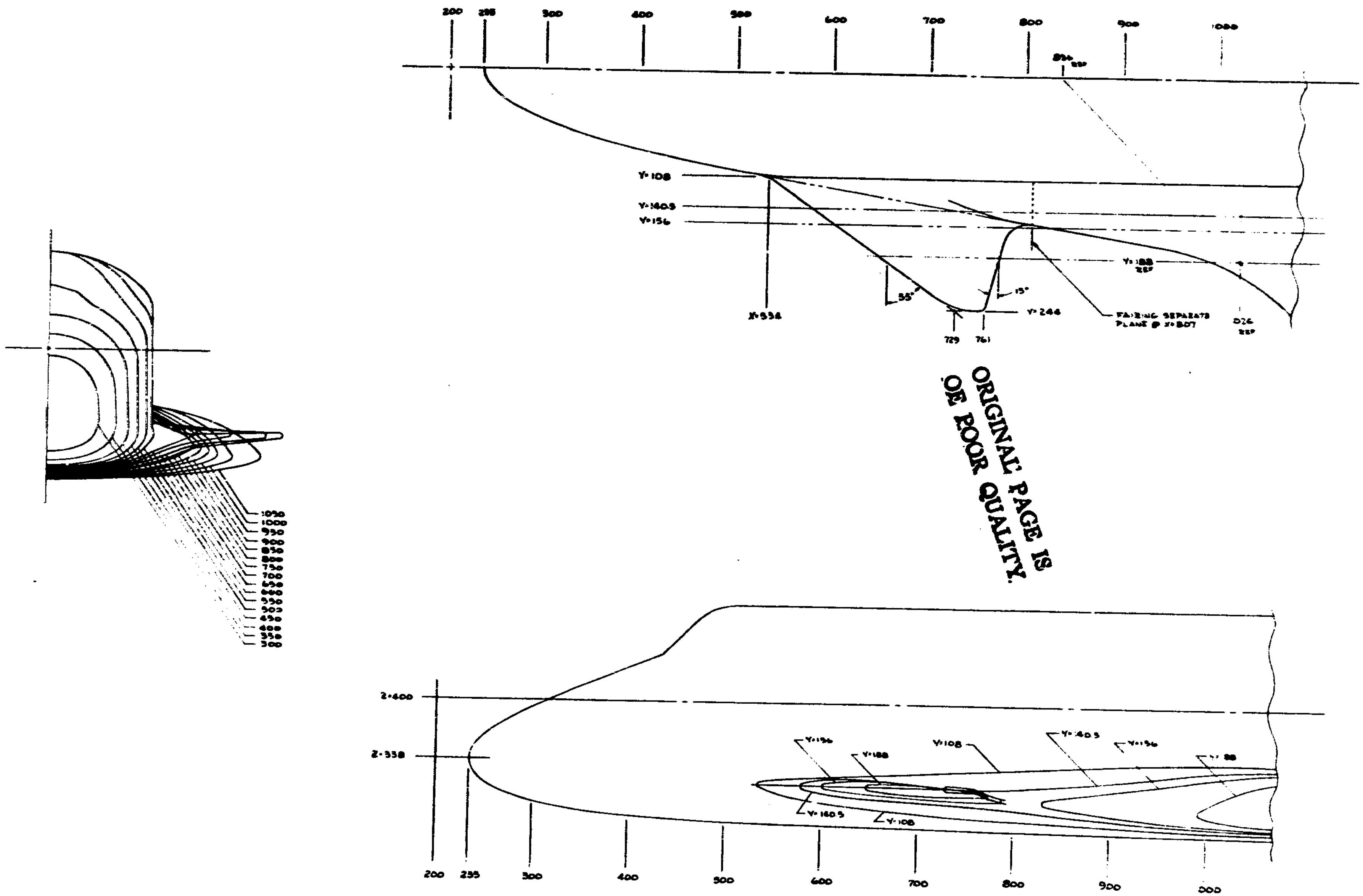
Figure 11 - Canard C2 designed to replace baseline fillet



(a) Systems changes and station locations
Figure 12 - Blended C-4 canard design

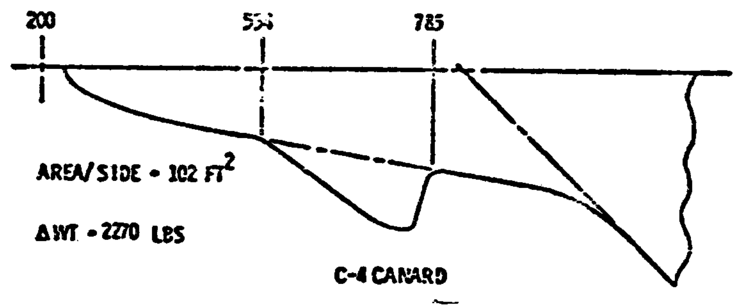


(b) Structural design
Figure 12 - Continued

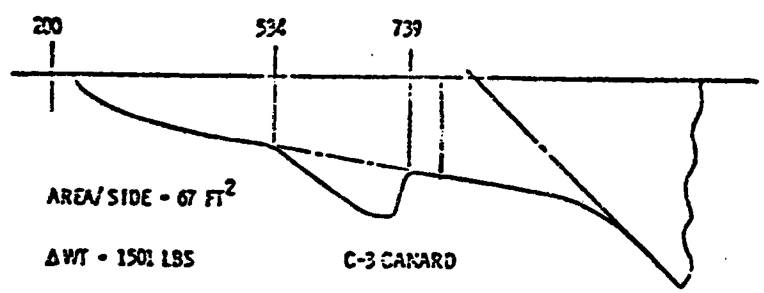


(c) Moldlines

Figure 12 - Concluded



(ORIGINAL DESIGN)



(C-4 RESIZED)

Figure 13.- Comparison of resized blended canard with the original study configuration.

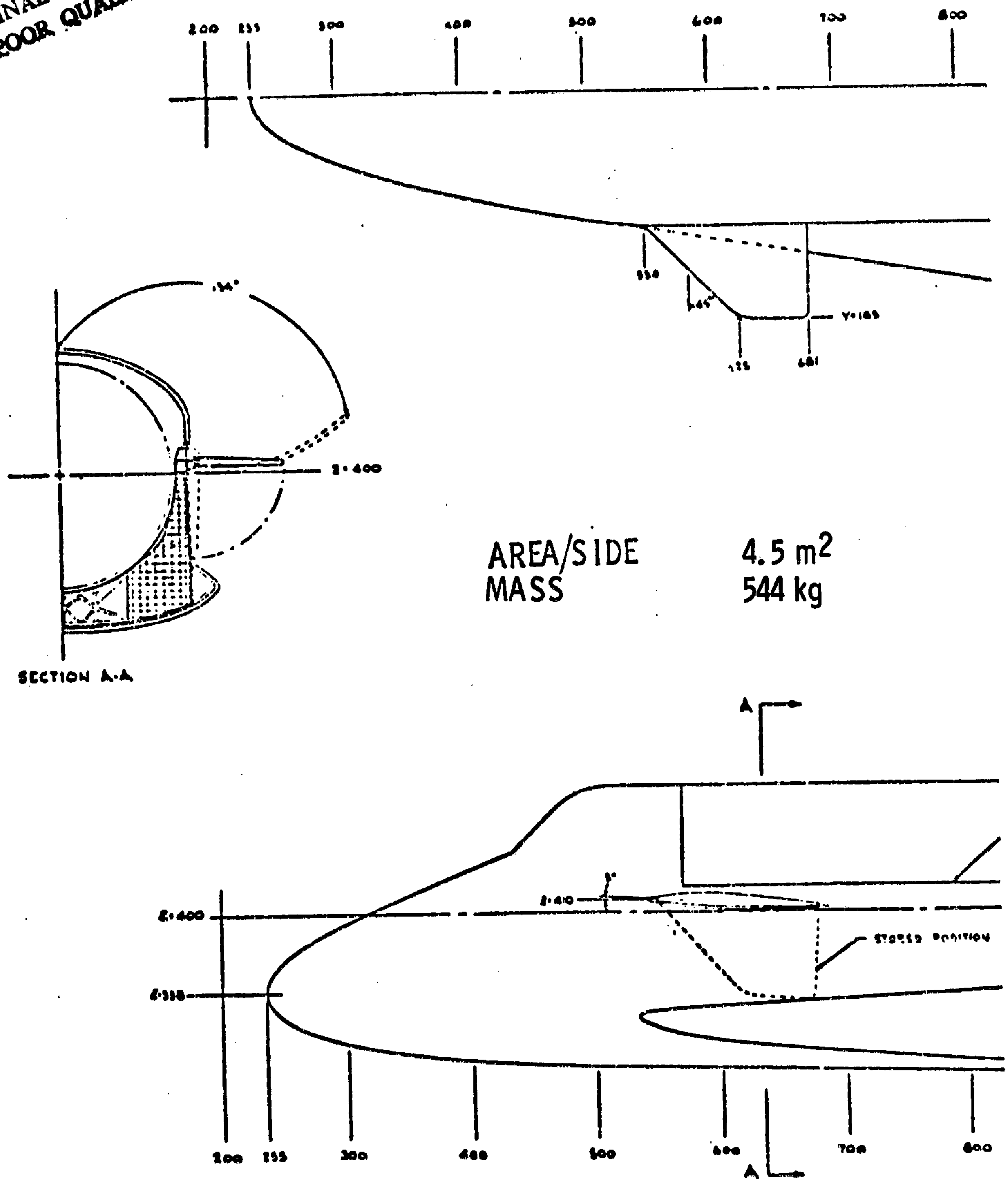


Figure 14 - Fold-down canard

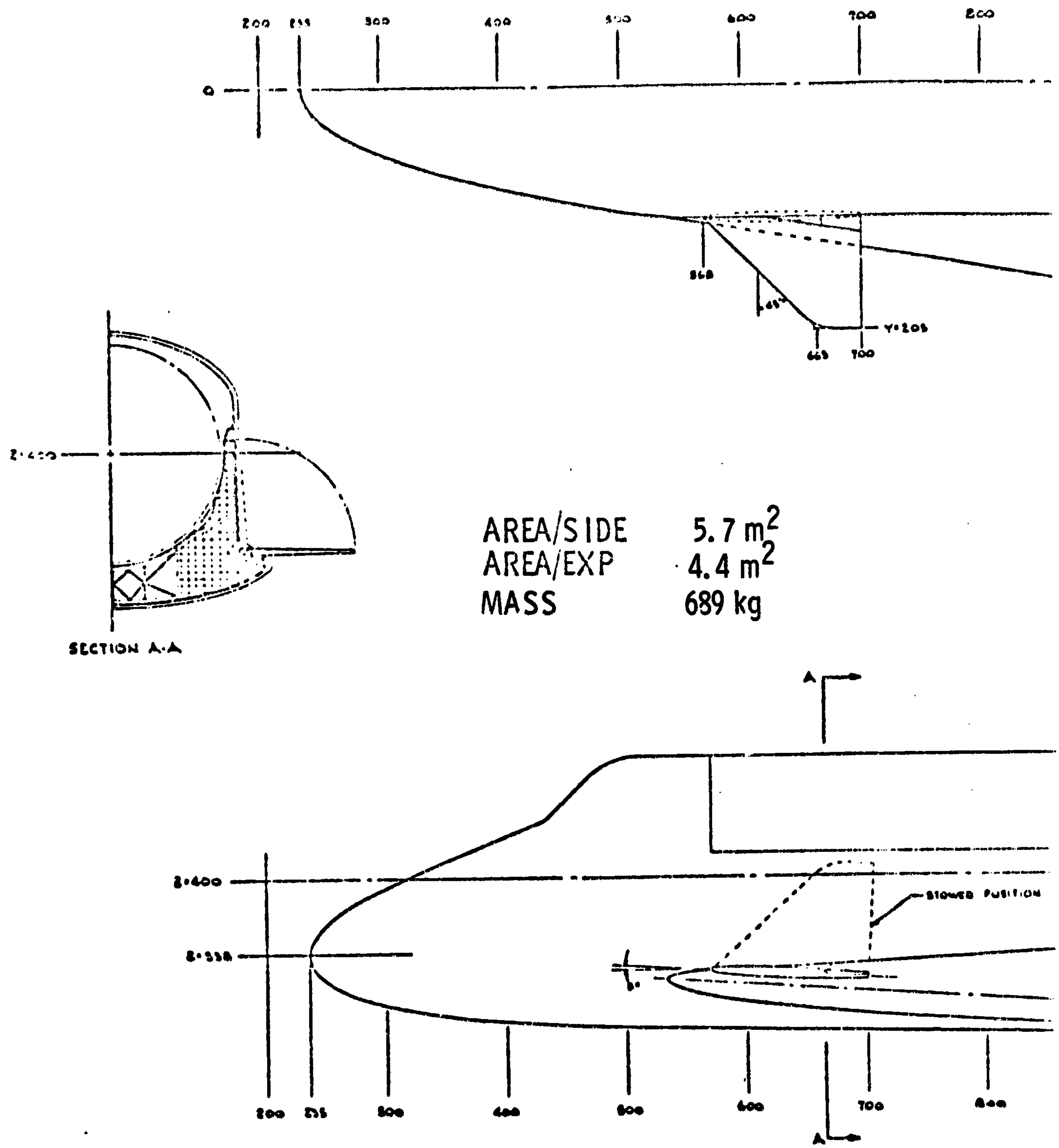


Figure 15 - Fold - up canard

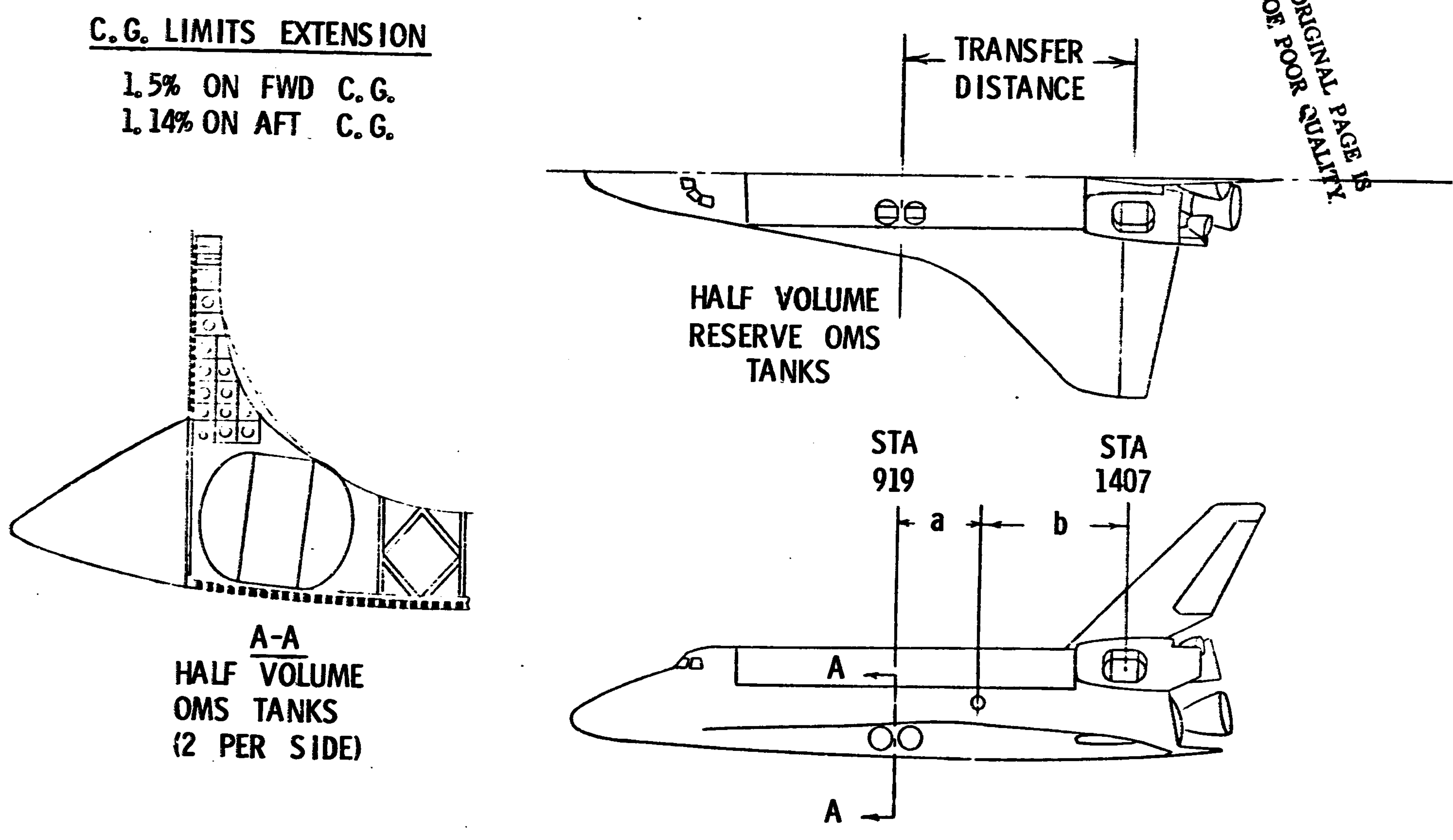


Figure 16 - Reserve OMS tanks for entry c.g. management.